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Optical methods of measuring loudspeaker diaphragm movement

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Summary

The principles of making measurements of the vibrational behaviour of lightweight diaphragms, using optical methods employing coherent-light interferometric techniques, are discussed. The use of a frequency-shifted reference beam (Doppler interferometry) is described, and simple methods of obtaining such a reference beam are considered. Results of measurements made on the diaphragms of loudspeaker drive units are discussed and methods of presenting these results are outlined.

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1. Introduction

Investigations into the vibrational behaviour of loudspeaker drive units, which is likely to be affected by any method of measurement relying on contact with the vibrating diaphragm ("cone"), have generated interest in the use of non-contact methods of measuring surface movement. Optical methods, relying on light reflected from the cone, clearly come within this category. Such methods of measurements usually rely on coherent-light interferometric techniques, in which the reflected light is combined with light from the same source travelling along an alternative path in such a way as to produce interference fringes: the behaviour of these fringes then provides the measure of surface movement. The use of coherent light enables interference fringes to be produced even when the two (or more) optical paths in the interferometer differ considerably in length, and in the present case a Helium-Neon laser (wavelength 633 nm) was used as the source of coherent illumination. Work has been carried out in this field elsewhere:[1-11] the purpose of the present investigation was to assess the effectiveness of different interferometric techniques in the context of a requirement for a measurement system which would be used relatively infrequently, and therefore for which high cost or complexity of operation could not be justified.

Since the scale against which the movement is measured, using interferometric techniques, is the wavelength of the coherent light in use, these methods of measurement are inherently very sensitive. This sensitivity is in fact sometimes an embarrassment, and steps have to be taken to control unwanted movement of the surface under measurement.

Some interferometric measurement techniques permit the detection of movement over the complete surface, while other methods measure the characteristics of surface movement at a particular point. Scanning techniques may be used in these latter cases to measure the behaviour of the whole surface.

Because loudspeaker cones are frequently made of materials having poor light-reflecting properties, a coating of highly reflective material is required in order to obtain clearly-defined interference fringes and the same time avoid the use of excessive incident light intensity. This does not represent a disadvantage, provided that the reflective material can be applied without affecting the acoustic properties of the unit.

In the first instance the uses of holography and speckle-pattern interferometry as methods of detecting motion over the complete surface of a loudspeaker cone were considered, and these methods are discussed in Sections 2 and 3 of this Report. The use of these methods was subsequently abandoned in favour of point-by-point measurements using a Michelson interferometric technique, and a simple single-line scanning system was developed for use with this arrangement. These developments are discussed in Section 4.

2. Holography

The principles of holography have been described in detail elsewhere[10] and by one of the authors of this Report[11] and only a summary is now given. Coherent light, scattered by an object whose image is to be recorded on hologram, is allowed to fall on to a photographic plate (Fig. 1). A "reference" beam of light of known geometry (e.g. collimated), derived from the same coherent source as is used to illuminate the object, is also allowed to fall onto the photographic plate. Interference takes place in the volume common to the radiation arriving by way of the two paths, and a cross-section of the interference pattern is recorded on the photographic plate. After processing, the information on the photographic plate is in the form of a fine pattern, which acts as a diffraction grating. When illuminated with a beam of identical wavelength and geometry to that of the original reference beam, one component of the diffracted light gives rise to a virtual image of the original object, occupying the same place in space relative to the processed photographic plate (the hologram) as did the original object.

If the object moves, the light and dark areas of the interference pattern will also move. With continuous illumination ("time-average" holography) this movement will blur the recorded pattern, and in this case a reconstructed image will only be obtained for stationary parts of the object. Holograms formed in this way will thus show the node-antinode pattern of the surface vibration but will give no information about the amplitude or phase of the surface movement. The fact that a reconstructed image only appears when the object is stationary immediately leads to problems concerning equipment and object stability. Suitable precautions (e.g. rigid construction and isolation from structural vibration) are required to prevent unwanted random changes in path length between the various components of the holographic recording system, while in addition unwanted acoustic excitation of the object must be prevented. With a large, light and relatively freely mounted object such as a loudspeaker cone this condition can be hard to achieve. Furthermore, a travelling-wave mode of vibration may sometimes be superimposed on the node-antinode vibration pattern, thus giving rise to movement over most of the cone surface. In these latter circumstances a system involving the introduction of a cyclic variation of path difference into the reference beam may be used[1]; image reconstruction occurs for object regions where this reference-beam modulation compensates for the object motion.

If illumination consisting of two pulses of light (each sufficiently short to "freeze" object motion*) is used, two holograms will be recorded, each hologram corresponding to the object position at the time of the corresponding pulse. If the object has moved so as to cause an optical path change of an even number of half-wavelengths between the occurrence of one pulse and the other, the two holographic interference patterns will reinforce each other and image reconstruction of this part of the object will occur. Movement of the object causing a path change of an odd number of half-wavelengths will give rise to two interference patterns which are out of phase and will therefore cancel each other on the recording. No image reconstruction will occur for such portions of the object. The overall effect is to produce a reconstructed image upon which is superimposed a fringe pattern. Any one fringe thus represents a contour of object movement along which the same change of optical path has occurred in the time interval between the two pulses. It may be noted that as this change in optical path depends on both the amplitude and the phase of the surface vibration at the time of occurrence of each pulse, it is not possible to obtain a separate measure of vibration amplitude and phase using only one double-exposure hologram. A distinction between the effects of vibration amplitude and phase can however be obtained by making a number of double-exposure holograms, using differing phase relationships between the two pulses of light and a suitable reference (say the loudspeaker excitation signal) in each case[2]. Even then a phase ambiguity of 180° remains, since it is not possible to tell which of the two possible positions was occupied by the object at the time of arrival of either light pulse.

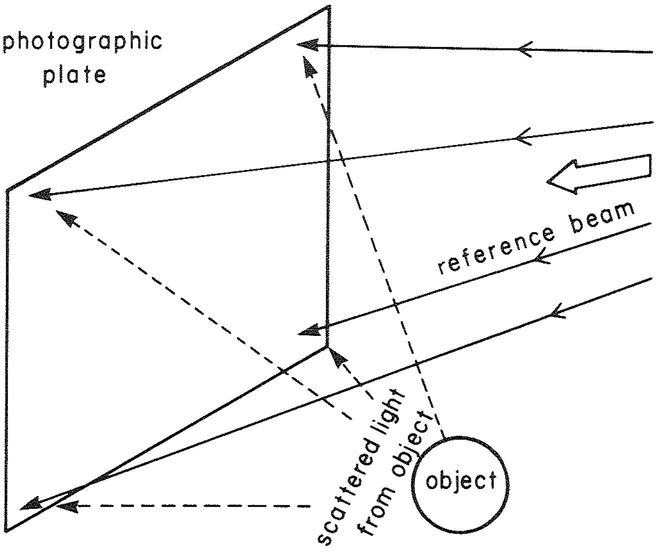

Fig. 1 – Illustration of holographic recording system. Object-illuminating beam not shown.

An advantage of time-average holography is that it can be carried out using relatively inexpensive "continuous-wave" lasers of modest output power. However, the problem of object stability makes this method of measuring loudspeaker diaphragm movement of doubtful usefulness. Double-exposure holography overcomes the stability problem, but the resulting contour fringe patterns are extremely hard to interpret. Furthermore, the type of laser required is expensive (by a factor of about ten compared with the requirements of time-average holography) and its high peak output power can give rise to a safety hazard. In both cases some form of processing is required before the reconstructed images can be observed (although alternatives do exist[11] to the use of photographic film). Since it was thought that these considerations precluded the use of holographic techniques as a routine method of measuring loudspeaker diaphragm movement, no further investigation was made of them.

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*The fringe motion should be less than about one-tenth of a fringe period, or object motion (see Equation 1, Section 4.3) less than 1/20 of a wavelength (i.e. 32 nm using Helium-Neon radiation). For an object having a velocity of 1 m/s this corresponds to a pulse length of 32 ns.

3. Speckle pattern interferometry

Speckle pattern is a random granular pattern which appears whenever coherent light is used to illuminate a rough surface. It is a result of interference between components of the light reaching the observer by way of a number of paths of different length, due to the surface roughness. The coarseness or "scale" of the pattern is a function of the aperture of the imaging system used to form an image of the surface, the average size of an individual "speckle" being of the same order as the central area of the diffraction pattern (the Airy disc) formed by the system. Thus the pattern becomes coarser (or in other words the scale increases) as this aperture is reduced.

For movement of a surface normal to the axis of observation the speckle pattern will appear to move bodily in the same direction as the surface movement. Movement of the surface along the axis of observation will have little effect on the speckle pattern and its structure will remain largely unchanged, unless a reference beam is present. In this case the intensity at a point in the field of view depends on the relative phase of the light from the surface and from the reference beam at that point, bright and dark speckles respectively representing points at which constructive and destructive interference takes place. A change of half a wavelength in the path difference between the two light paths will cause the positions of bright and dark speckles to be interchanged. Surface vibration with amplitude sufficient to produce this path change will thus blur out the speckle pattern and cause it to disappear. The speckle pattern will only remain visible at the vibration nodes.

An instrument which enables a reference beam to be introduced, so as to exploit this effect, has been described by Stetson[3] and a version of this arrangement was constructed (Fig. 2). In it, light from a laser is split into two components of unequal intensity using a partially reflecting surface, not shown in the Figure. The component of greater intensity is used to illuminate the surface under examination, using a mirror M to obtain normal incidence, while the component of lesser intensity is introduced as the reference beam. The vibrating surface VS is observed along its direction of movement through a hole in the centre of mirror M, using lenses L_1 and L_2 which are arranged to behave as a telescope of unity magnification. A pinhole P, placed at the focal point of lens L_1, restricts the aperture of the instrument and gives a suitable scale of speckle pattern. The reference beam is introduced by reflection from one surface of a wedge-shaped beam-splitter S, reflection from the other surface being arranged to fall outside the field of view. A polarizing filter (F_1) is used to define the plane of polarization of light reflected from the surface under investigation, and a similar filter (F_2) defines the plane of polarization of the reference beam. These two planes of polarization should be parallel. A third rotatable filter in the reference beam (F_3) can be used to adjust the

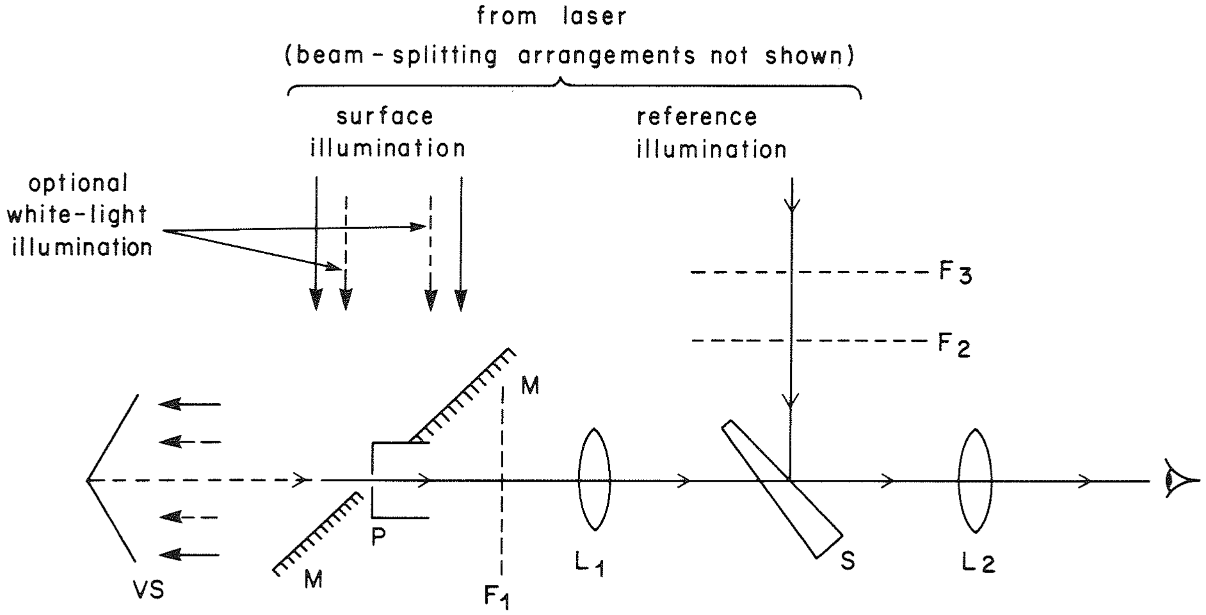
from laser
(beam - splitting arrangements not shown)
surface illumination
reference illumination
optional white-light illumination
F3
F2
M
VS
M
P
F1
L1
S
L2

Fig. 2 – Experimental arrangement for speckle pattern interferometer.

reference beam intensity. In the absence of these polarizing arrangements, good integration of the speckle pattern with surface movement is not obtained, and some speckle remains visible at all times. Careful alignment of the axes of propagation of the light from the object and in the reference beam is also necessary to achieve good speckle-pattern visibility.

With the intensity of the reference beam adjusted so that speckle pattern is easily visible in the absence of surface vibration but not when the surface is in motion, the field of view appears to be uniformly illuminated (due to the reference beam) with the speckle pattern embedded in it. Using only laser illumination the surface under test is not visible as its luminance as seen through the equipment is considerably lower than that of the reference beam. It may however be rendered visible by illuminating it with white light in addition to the laser illumination, and in this condition the vibrational modes revealed by the presence of speckle pattern can be related to position on the surface itself.

A disadvantage of all instruments which use accurately collimated or "parallel" light is that opaque objects in the optical path (e.g. blemishes on the optical surfaces) cast sharp shadows, even though they may be in a part of the instrument in which they would nominally be out of focus. The fluids bathing the surface of the eye and in the vitreous cavity of the eye itself often contain suspended particles (floaters) and shadows of these objects can also appear in the field of view. Further non-uniformities in the field-of-view illumination can be caused by interference effects involving coherent light scattered by these objects. Speckle-pattern visibility will be affected by all such effects.

By using a monochrome television camera in place of the observer, video signal processing can in principle be used to enhance the speckle pattern visibility and remove the bright background in the field of view produced by the reference beam, and also eliminate difficulties caused by the eye defects mentioned above. Work in this field has been carried out by Butters and Leendertz[4], and a commercially-available instrument employing this technique is now available. Unfortunately, because of the restricted aperture required to produce a speckle pattern of a suitable scale, the area of the surface that can be examined with such equipment is considerably smaller than that required for the assessment of low-frequency loudspeaker units, if the power of the laser used as the light source is restricted to a reasonable value (say 5 mW). Furthermore, the node-antinode patterns of cone vibration may again be obscured by the presence of a travelling-wave component, as discussed in Section 2.

As in the case of time-average holography, suitable precautions must be taken to eliminate unwanted changes in optical path length between the various components of the equipment. The stability required is perhaps not quite as stringent as in holography, since very slow changes in optical path difference cause an overall "crawling" of the speckle pattern, without however causing it to disappear completely. With the adoption of these precautions, speckle-pattern interferometry can, in principle at least, give an overall picture of the standing-wave vibrational pattern. It is not readily adaptable to giving quantitative information on the magnitude or phase of the surface movement, and it is difficult to obtain results other than by direct visual observation, thus making the recording of these results inconvenient. These factors, coupled with the possible masking of conventional standing-wave patterns by superimposed travelling waves, have led to the abandonment of this line of approach to the measurement of the vibrational behaviour of loudspeaker drive units, in favour of the Michelson interferometry technique discussed below.

4. Michelson Interferometry

4.1. Comparison with other types of two-beam interferometer.

Three basic forms of two-beam interferometer[12a] employing fully-reflecting and partially-reflecting ("beam-splitting") mirrors may be distinguished (Fig. 3). Both the Mach-Zehnder and Michelson arrangements (Figs. 3a and 3b) can be used to measure the relative translational movement of the fully reflecting mirrors M_1 and M_2. These arrangements differ in that the Mach-Zehnder form enables any non-normal angle of incidence onto the fully-reflecting mirrors to be accomodated, while the Michelson form only permits normal incidence of light onto the fully-reflecting mirrors to be used. For completeness the Sagnac configuration is also shown (Fig. 3c): this is sensitive only to movement of the partially reflecting element and is used to measure rotary motion about an axis normal to the plane of the interferometer.

The Michelson rather than the Mach-Zehnder arrangement has been chosen for the present application since it uses fewer optical components and because the direction of surface movement

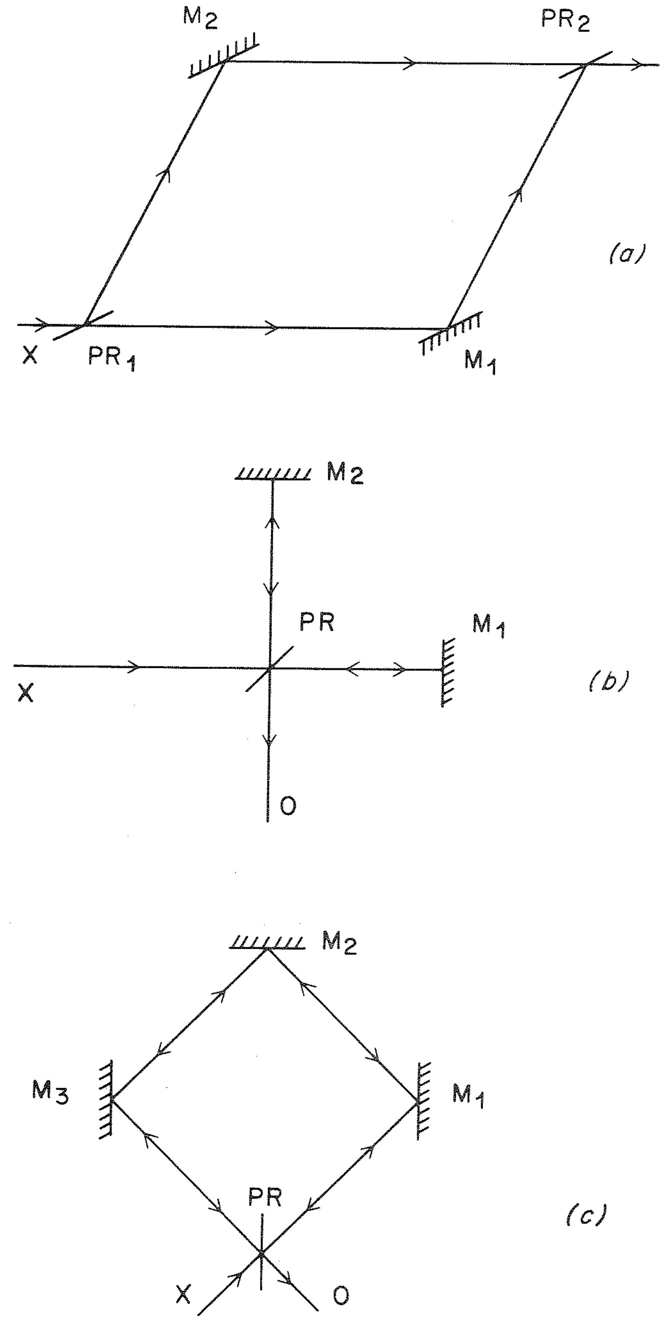

Fig. 3 – Forms of two-beam interferometer.
(a) Mach-Zehnder: (b) Michelson: (c) Sagnac:
Pr – Partially-reflecting mirror;
M – Fully-reflecting mirror;
X – Source of radiation;
O – Observer.

which is measured (along the optical path) is well-defined. Other workers in this field[5,6,7,8] have also found this arrangement convenient. Modifications are however required to the simple arrangement shown in Fig. 3b, because the direction of motion of a loudspeaker diaphragm is often not normal to its surface, and because the diaphragm is usually a diffuse rather than a specular optical reflector: these are discussed below.

4.2. Optical Techniques

The process by which interference fringes are generated in the Michelson interferometer is described in detail elsewhere[12b]. In the present case it may be noted that, if the source of radiation emits a collinear* beam, then a set of annular fringes may be observed if the radiation emerging from the beam-splitter in the direction of the observer (0, Fig. 3b) is intercepted by a screen. The spacing of the fringes decreases with distance from the centre of the pattern, the radius of the nth fringe from the centre being proportional to $\sqrt{n}$. The constant of proportionality in this relationship (or "scale" of the pattern as a whole) depends on the optical path difference in the interferometer: the scale decreases as this path difference is increased.

The intensity of the radiation at the centre of the fringe pattern will depend on the phase difference between the components reaching this point by way of the optical paths in the interferometer. A change in path difference by one radiation wavelength will therefore cause the intensity to exhibit one cycle of variation, passing through maximum and minimum values and returning to the original value. A change in the interference pattern scale will also take place, as discussed above.

Instead of observing the interference pattern visually, radiation from near the centre of the pattern (selected by an aperture of suitable size) can be used to excite an electrical photoreceptor, whose output will be the analogue of the radiation intensity at the pattern centre. Thus, if one mirror of the interferometer (say M_1) is attached to the surface whose behaviour is to be examined, and the other (M_2) remains stationary to provide a constant reference path length, then

$$l = \frac{N\lambda}{2} \qquad (1)$$

where l is the distance moved by mirror M_1 and N is the number of cycles in the photoreceptor output-signal waveform. Fig. 4 shows the photoreceptor output-signal waveform under such conditions. It can be seen that the surface movement causes seven cycles of intensity variation to occur. With $\lambda = 633\,\text{nm}$ (Helium-Neon laser radiation)

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* The term "collinear" is used to include converging or diverging beams consisting of concentric spherical wave-fronts, of which the parallel "collimated" beam consisting of plane wave-fronts is a special case.

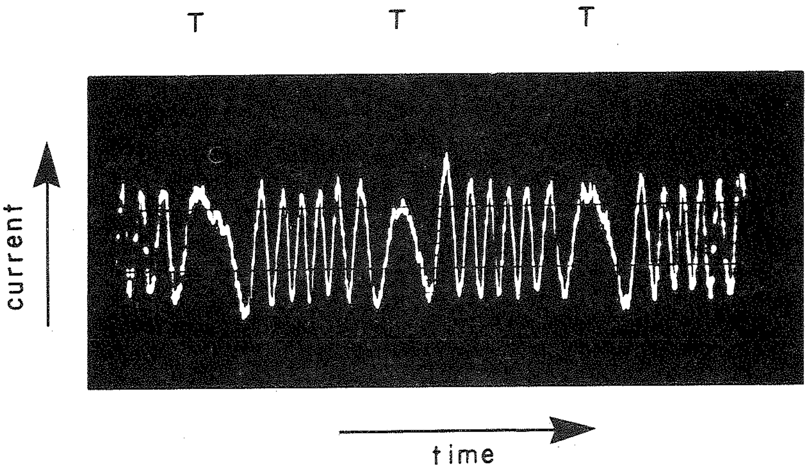

Fig. 4 – Example of photoreceptor output-signal waveform, using stationary reference surface.

Equation 1 shows that the peak-to-peak surface displacement is 2.2 μm. The timing of the turning points of the surface movement (T, T, . . . in Fig. 4), relative to a reference such as the loudspeaker excitation signal, provides a measure of the phase of the movement. This phase measurement is subject to a 180° ambiguity since the direction of motion of the surface is not indicated by the photoreceptor-signal waveform.

A modification to the simple system shown in Fig. 3b permits the use of a diffuse reflecting surface in place of a specularly-reflecting mirror in either or both arms of the interferometer. The principal advantage of this arrangement is that it enables measurements to be made directly on diffusely-reflecting vibrating surfaces, without the need for arranging for specular reflection. Additionally, it enables a simple form of moving surface to be used to provide Doppler frequency shift (see below). Fig. 5 shows the arrangement, used to obtain the results discussed in Section 5 of this Report, in which both test and reference mirrors have been replaced by such surfaces (S_1 and S_2). The lenses L_1 and L_2 are placed so that S_1 and S_2 respectively are near their focal planes. The unexpanded laser beam is brought to a focus on each surface by its associated lens, and the very small illuminated areas of these surfaces act, in principle at least, as isotropic point radiating sources. Light reflected back towards each lens will thus emerge from it as a collinear beam. The resulting interference pattern again consists of annular fringes. Radiation from the pattern centre is selected by the aperture A and excites the photoreceptor P. The output-signal waveform of the photoreceptor is again related to test-surface movement by Equation 1, with the reference surface stationary.

Because in fact the illuminated areas of the diffusely-reflecting surfaces are of finite extent, distortion of the annular interference pattern will occur because of small irregularities in the path difference over these areas (which are "rough" in optical terms). The size of the aperture A has to be chosen to accommodate this effect and yet still resolve the fringe pattern. In practical terms this means that the aperture must be smaller than would be necessary if the interference pattern was not distorted or "broken-up" in this way. A small aperture is also required to resolve the centre of the fringe pattern (and thus enable the interferometer to continue to function) in cases where the distance of the test surface from the instrument changes

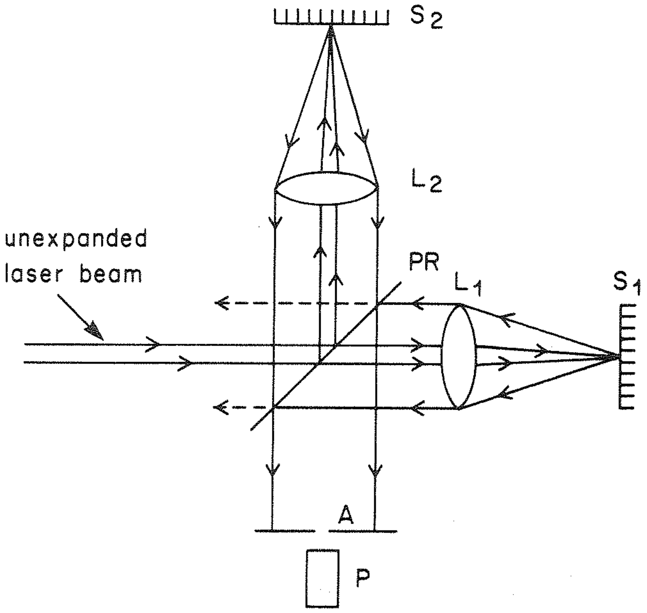

Fig. 5 – Michelson interferometer with diffuse reflecting surfaces.

considerably during the course of a measurement*. Such changes in distance can for example occur when measurements are made sequentially at different positions on a loudspeaker diaphragm, using the scanning techniques discussed in Section 4.4. Too small an aperture, on the other hand, will result in a photoreceptor signal having poor signal-to-noise ratio, and a compromise has to be reached in this respect. In the experimental arrangement a "depth of field" of some 35 mm was obtained. This was adequate for scanning across a low-frequency loudspeaker unit of 200 mm diameter. The profile of a unit having a diameter of 300 mm could also be accommodated if care was taken to position the interferometer so as to minimise the changes in distance of the cone of the unit from the interferometer.

A completely unambiguous representation of the movement of the test surface may be obtained by imparting a continuous motion to the reference surface[9]. If the magnitude of the (constant) surface velocity is $|v|$, then the distance (l) it moves in time t is $|v|.t$ and substitution for l in Equation 1 gives

$$|v| = \frac{N\lambda}{2t} = f\frac{\lambda}{2}$$

where f is the frequency of the alternating component which appears in the photoreceptor output waveform. Hence

$$f = \left|\frac{2v}{\lambda}\right| \qquad (2)$$

Equation 2 may also be derived by considering the light reflected from the moving surface as shifted in frequency due to the Doppler effect (reflection in a surface moving with velocity v is equivalent to emission from a source moving at a velocity of $2v$): this gives rise to the generic term "Doppler interferometry" for techniques involving moving surfaces. When both the surfaces are in motion, the frequency of the photoreceptor output signal indicates the instantaneous sum of the velocities of these surfaces. Thus the "carrier" due to motion of the reference surface is frequency modulated by the motion of the test surface, and a suitable detection arrangement can be used to recover an audio-frequency signal which is an analogue of the test surface velocity. The velocity of the reference surface must at all times be greater than that of the test surface in order to preserve a one-to-one correspondence between the test surface velocity and the photoreceptor-signal frequency.

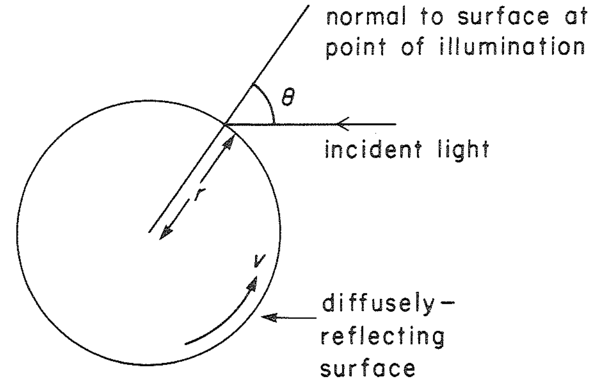
normal to surface at point of illumination
θ
incident light
r
v
diffusely-reflecting surface

Fig. 6 – Geometry of illumination of cylindrical surface.

In the experimental arrangement the moving reference surface was provided by off-axis illumination of the periphery of a diffusely-reflecting rotating cylinder[13] (the spindle of a small, accurately-constructed electric motor coated with magnesium oxide). The geometry of the arrangement is shown in Fig. 6. It can be seen that the velocity along the direction of incidence is given by

$$v = \frac{\pi r R}{30}\sin\theta \qquad (3)$$

where r is the radius of the cylinder and R its rotational speed in revolutions per minute (rpm). In the present instance the motor revolved at 1500 rpm and the radius of the shaft was 4 mm: if $\theta = 45°$, then $v = 0.44\,\mathrm{ms}^{-1}$ from Equation 3, and the carrier frequency f in the photoreceptor output signal is 1.4 MHz from Equation 2. This value of peak velocity would allow measurements to be made on a 300 mm low-frequency loudspeaker unit housed in a suitable enclosure giving a sound pressure level of about 94 dB* at 100 Hz (at a distance of one metre), or on a high-frequency unit 34 mm in diameter giving a sound pressure level of 90 dB at 2 $\mathrm{kH_z}$ and at one metre. These sound pressure levels correspond to typical listening levels and units can therefore be examined under normal operating conditions.

A disadvantage of using a moving diffuse reference surface is that it introduces a random fluctuation of reference-beam intensity. This in turn introduces a random-noise-like component into the photoreceptor output signal. Despite this, a system output signal-to-noise ratio in excess of 45 dB has been achieved, relative to the signal from a surface moving at the greatest measurable velocity. This is due to the inherent immunity from amplitude fluctuations given by the use of frequency modulation, and also to the use of suitable filtering arrangements (see Section 4.3). This performance is more than adequate for carrying out diagnostic tests on loudspeaker units. It may also be noted that the process of scanning the point of observation across the loudspeaker diaphragm (see Section 4.4) would also introduce noise-like components of a similar level into the photoreceptor signal. If the use of this technique is envisaged there is little point in achieving better intrinsic noise performance by using a more sophisticated method for frequency-shifting the reference radiation.[13]

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* Fringe pattern scale is more sensitive to surface movement when diffusely-reflecting surfaces are involved rather than specularly-reflecting mirrors.

* Relative to 20 μPa r.m.s.

In the experimental arrangement the beam-splitting mirror and the two lenses (see Fig. 5) were mounted in one unit with arrangements for their accurate and consistent alignment. The unit carried an additional mirror (not shown in Fig. 5), adjustable in azimuth about vertical and horizontal axes, for "folding" the path of the beams leaving the interferometer so as to be parallel to the beam from the laser entering it. This gave a more compact equipment arrangement while at the same time providing a convenient method of centering the interference pattern on the photoreceptor input aperture. The lenses were arranged to be slightly off-axis with respect to the beams passing through them, so that light returned from their surfaces did not enter the photoreceptor. Coherent radiation was provided by a 1 mW Helium-Neon laser, and a photomultiplier having a trialkali (S20) photocathode was used to provide good sensitivity to red light: control of the potential applied to the photomultiplier dynode chain was used to set the output signal current. The input aperture was 1.5 mm in diameter. Fig. 7 illustrates the equipment and shows details of the moving reference surface,

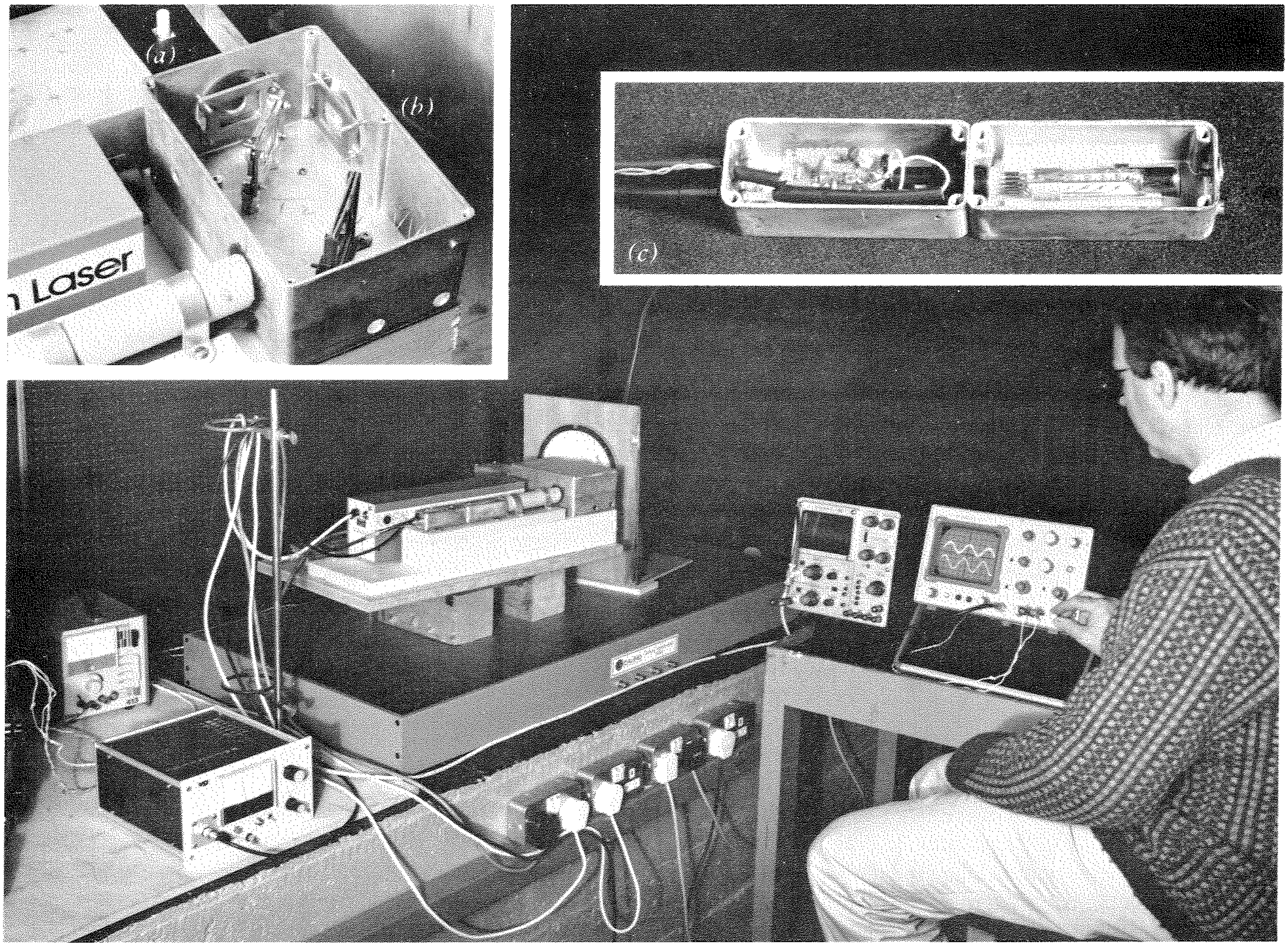


Fig. 7 – Interferometric vibration-measuring equipment.
(a) moving reference surface;
(b) lens and mirror assembly;
(c) photomultiplier and head amplifier assembly.

the lens and mirror assembly and the photomultiplier assembly. The measurements involving the scanning of the loudspeaker unit (see Section 4.4) were obtained by supporting the complete interferometer on a freely-rotating turntable, and rotating it about a vertical axis at constant speed.

4.3. Electronic instrumentation

The Michelson interferometer provides as its output a frequency modulated signal whose deviation from centre frequency is a direct measure of the velocity at which the object under study is moving. Suitable processing, of the form shown in Fig. 8, provides voltages which can be fed to a plotter and which represent separately both the magnitude of the loudspeaker velocity and its phase relative to the drive voltage. These may be plotted as functions either of frequency at a fixed point on the loudspeaker diaphragm, or of position on the diaphragm at a fixed frequency.

The photomultiplier behaves as a current source, the output signal being of the order of a few microamperes. As the anode is at earth potential a virtual-earth amplifier may be used to obtain a more convenient signal level and source impedance.

The amplified signal, whose centre frequency in the prototype interferometer is about 1.2 MHz, is then bandpass-filtered to allow a peak-to-peak deviation of 1.4 MHz. By thus setting the lower band limit at about 500 kHz, most of the speckle-pattern noise previously mentioned is eliminated. The filtered signal still has very low signal-to-noise ratio (about 6 dB), and to extract the maximum amount of information, the waveform is "conditioned" by a phase-locked oscillator, whose output is then demodulated by a pulse-counting discriminator. It is difficult to obtain a voltage-controlled oscillator whose transfer characteristic is not extremely non-linear over such a wide frequency range, and the addition of a pulse-counting discriminator in the form of a monostable is a simple means of providing an output signal which is much more linearly related to frequency than the oscillator control voltage.

The demodulated signal from the interferometer photomultiplier of the form $A\sin(\omega t + \phi)$ is in practice very noisy, and the accurate extraction of its amplitude (A) and phase (ϕ) therefore requires the use of a narrow-band tracking filter. Such a filter is normally implemented by frequency-shifting to DC, low-pass filtering, then frequency-shifting again to generate a "clean" version of the original signal, whose amplitude and phase are preserved in the process. A slight modification of this principle regenerates a signal of the correct amplitude and phase, but at a constant frequency, which makes further processing easier. This is shown schematically in Fig. 9. The low-pass filters reject the components at twice drive frequency ω, leaving only the sine and cosine components of the original signal. The complete circuit is exactly equivalent to a tracking filter whose bandwidth is twice that of the low-pass filters, in conjunction with a frequency-shift to a constant frequency ω_0.

It is very readily shown that this principle can be extended to the use of switches driven by square-wave reference signals, provided that a final low-pass filter is added as shown in Fig. 10. The advantage of conversion to a fixed frequency now becomes apparent because it means that the final low-pass filter is required only to reject the third and higher harmonics of the fixed frequency ω_0.

In the prototype interferometer the bandwidth of the tracking filter is about 2 Hz, which provides a signal-to-noise ratio of more than 45 dB at full deviation, whilst still accommodating adequate rates of audio frequency sweep.

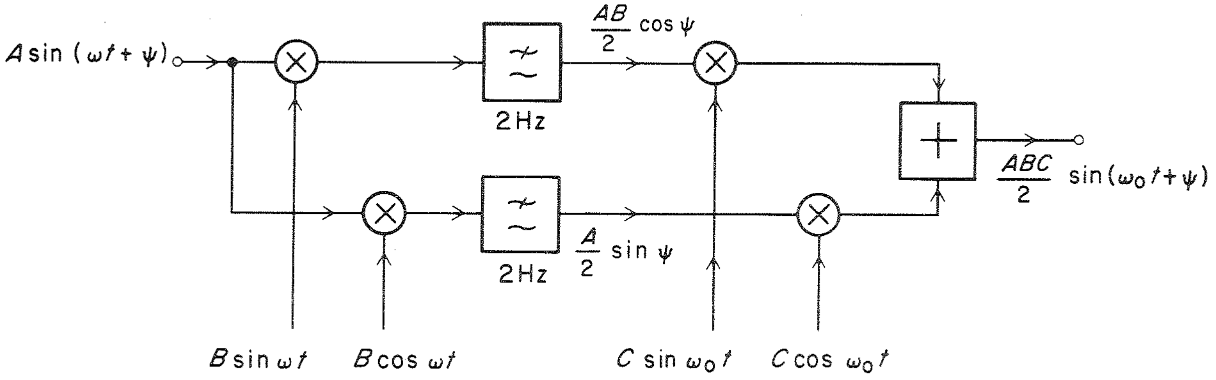


Fig. 8 – Schematic of complete signal processor for Michelson interferometer.

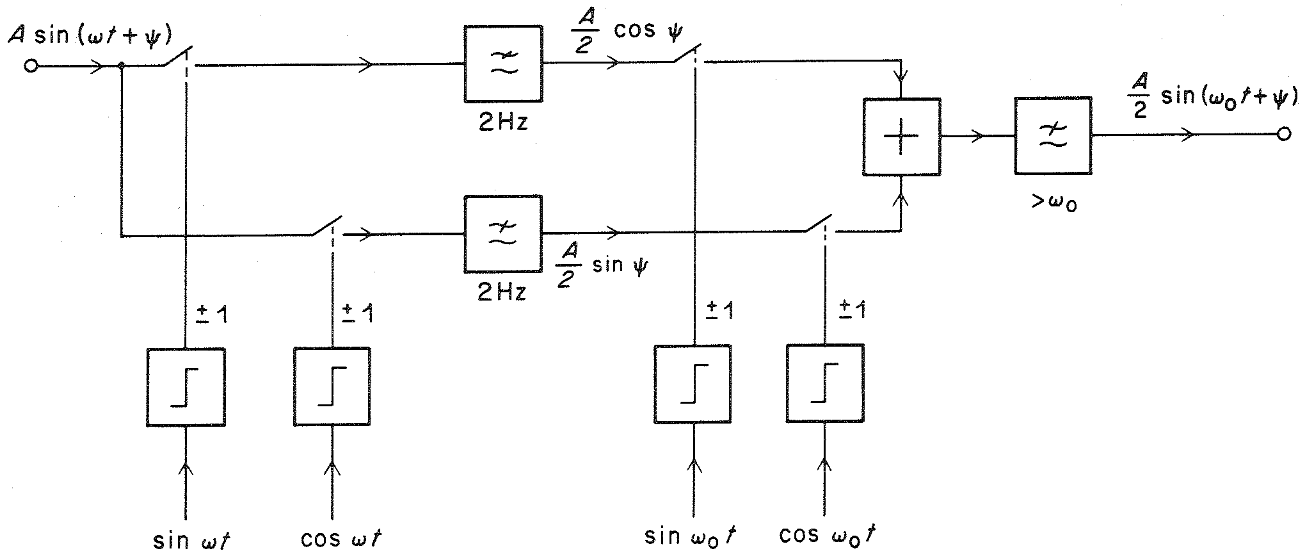


Fig. 9 – Tracking filter with change to constant frequency.

Finally, it is worth noting that this type of tracking filter is readily adapted to admit any chosen harmonic instead of the fundamental of the loudspeaker drive signal. This facility may well be incorporated into later versions of the equipment.

4.4. Discussion

During development of the overall system two sets of measurements were made of the amplitude of vibration of a surface, using a stationary reference surface. In the first of these sets the interference pattern was observed visually, and the excitation of the loudspeaker unit under investigation was increased from zero until the fringe pattern visibility was at a minimum. The path length introduced by the surface movement was then half a wavelength of the light in use (see Section 2) and the peak-to-peak surface movement was therefore a quarter wavelength (158 nm, using Helium-Neon radiation). The frequency characteristic of the unit was obtained from the reciprocals of the excitation level values. This technique was applied to the measurement of a high-frequency loudspeaker unit consisting of a hemispherical diaphragm of piezoelectric plastic material[14]: the form of Michelson interferometer using specularly reflecting mirrors (Fig. 3b) was used, since the surface of the unit was specularly reflecting and since measurement of the amplitude of vibration normal to the diaphragm was required. Sufficient isolation of the equipment from structural vibration was provided to enable spurious fringe-pattern perturbations to be identified visually. In the second set of measurements the fringe counting technique was used to examine the behaviour of the diaphragm of a 200 mm low-frequency unit, using the equipment arrangement shown in Fig. 5. Although the movement of the diaphragm was considerably larger than in the measurements

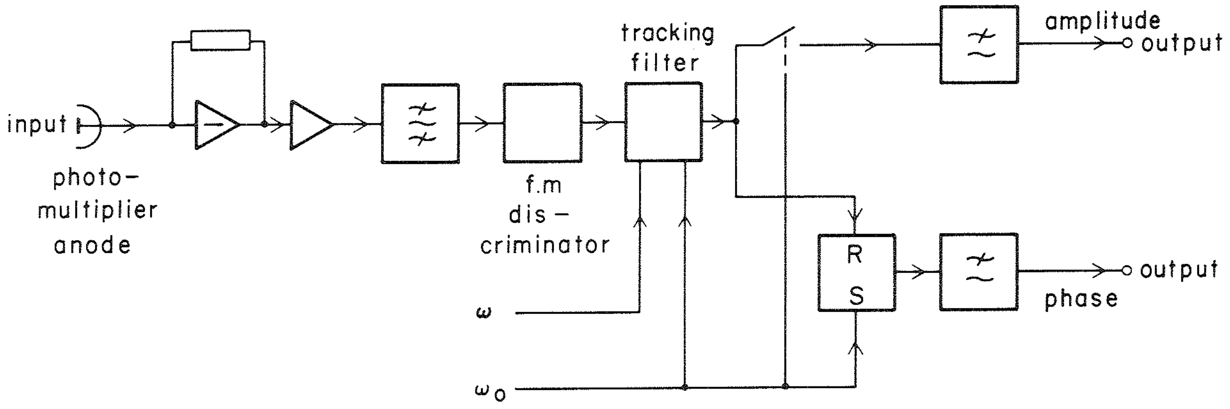
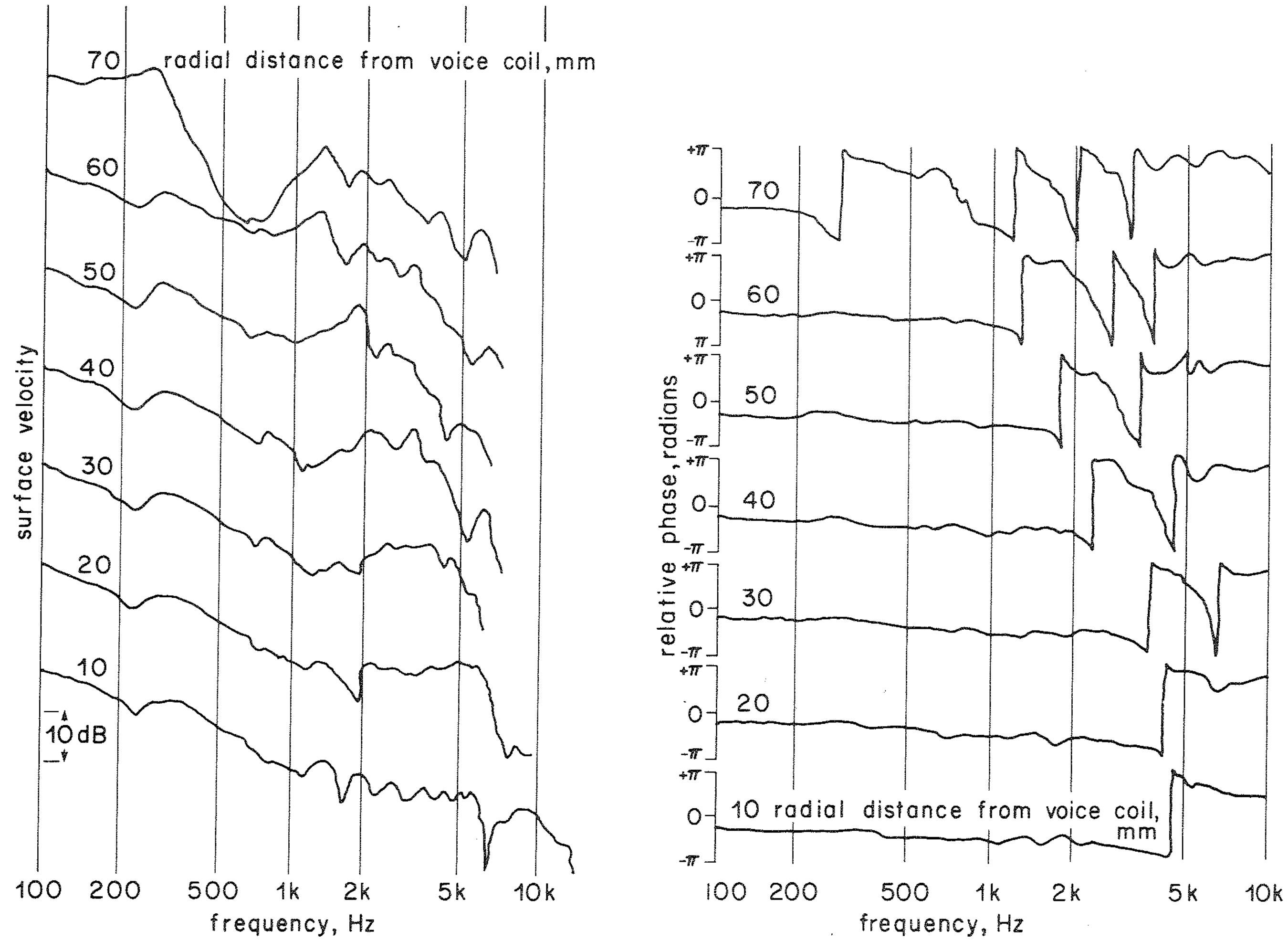


Fig. 10 – Tracking filter using switches instead of multipliers.

described above (a count of ten fringes, for example, corresponded to movement of some 6.3 μm), observation of the waveform of the photoreceptor output signal was made difficult by the presence of spurious perturbations of the fringe pattern, even though isolation of the equipment from structural vibration was provided. A rolling display using a digital storage oscilloscope was therefore used, the trace movement being frozen to count the fringes.

The measurement techniques using a stationary reference surface, described above, would both be satisfactory for examining vibrational behaviour in cases where the number of measurements is small, and where information on vibrational phase either is not required or can be accepted with a 180° ambiguity. Because of the need for direct visual observation, however, neither method is well suited to the thorough investigation of a surface such as a loudspeaker diaphragm, where a large number of measurements are required both to accommodate the detailed pattern of vibration over the whole surface and to investigate the changes in this pattern with frequency. The use of a moving reference surface as discussed in Section 4.2, together with the circuit arrangements described in Section 4.3 (see Fig. 10), enables signals to be derived representing both the magnitude of surface velocity and also its phase relative to the loudspeaker excitation signal. With the addition of a swept oscillator and pen recorder, families of curves of the form shown in Fig. 11 can be obtained. Each such curve shows the magnitude (Fig. 11a) and phase (Fig. 11b) of the surface velocity as a function of excitation frequency. The uppermost curve refers in each case to a point near the outer edge of the diaphragm of a low-frequency loudspeaker unit, while the lowermost curve refers to a position near the voice coil. In all cases the



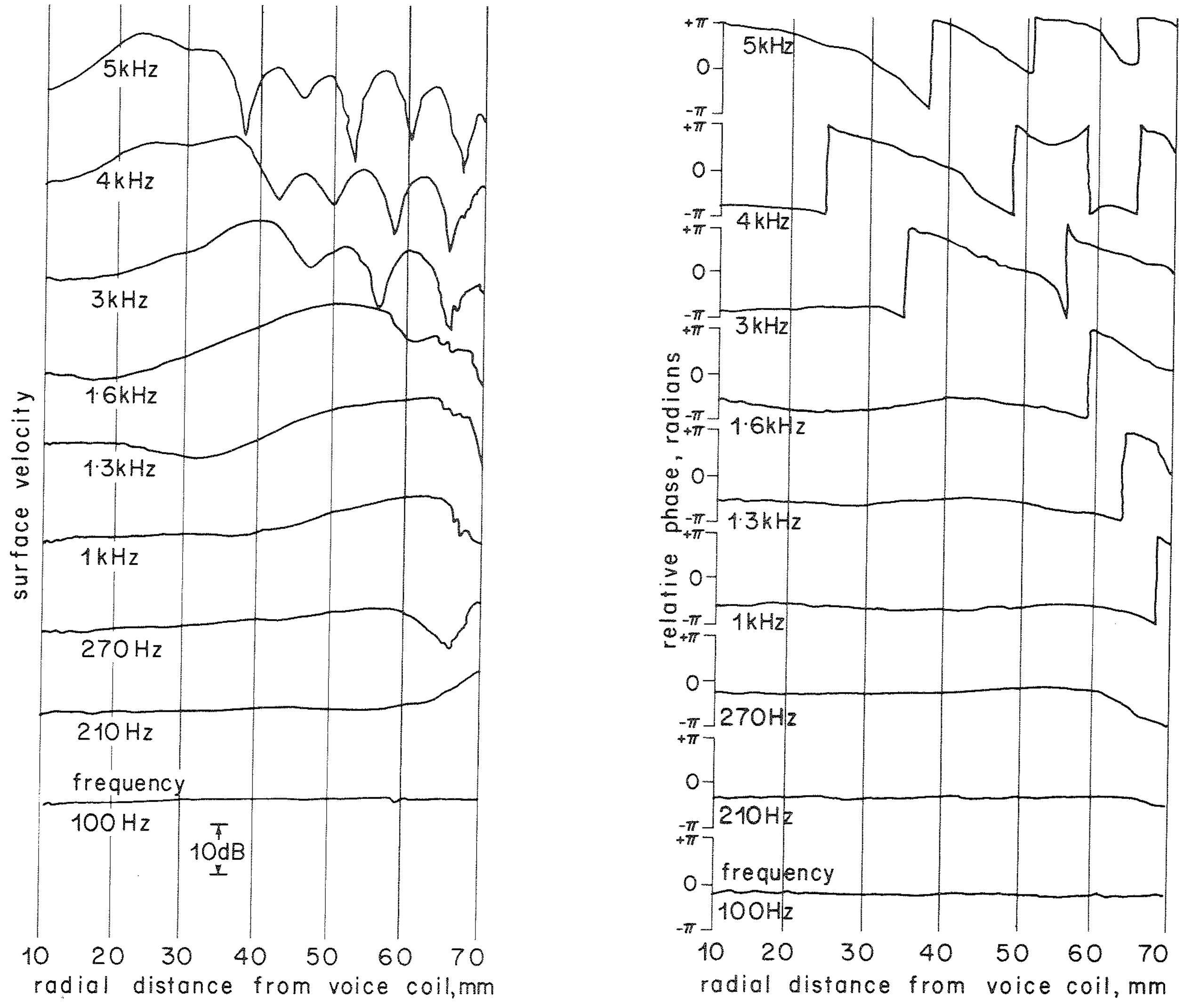
(a) (b)

Fig. 11 – Plots of velocity vs. frequency for a low-frequency drive unit driven at constant voltage. (a) magnitude (logarithmic scale: curves displaced by 20 dB); (b) phase. Each curve is identified by the radial distance of the point of measurement from the voice coil, in mm. Vertical spacing between plots is for clarity only.

component of vibration along the axis of the unit was measured. The most prominent feature of the unit on which these measurements were made was the fundamental " umbrella" mode of the diaphragm and surround, which occurs at about 270 Hz. This caused a peak in velocity at all the points measured (see Fig. 11a), but it is clear from the phase plots of Fig. 11b that the outer periphery of the diaphragm was moving in antiphase relative to the centre, and that a node must have existed at a radial distance of about 65 mm from the voice coil.

An alternative and probably more useful method of displaying this information is to move the light spot along a radius of the diaphragm whilst keeping the frequency constant. The prototype interferometer did not incorporate scanning mirrors, but by placing it on a turntable and rotating it by a small electric motor, a set of positional scans was obtained for a number of excitation frequencies as shown in Fig. 12a (velocity magnitude) and 12b (phase). These plots show very clearly the 270 Hz diaphragm mode, with its node and phase inversion 65 mm outwards from the voice coil. There appear to be no other modes up to 1.6 kHz; this may be seen from the magnitude plots, while the phase plots show, by their monotonic slope, that energy is being propagated radially outwards from the voice coil in the form of travelling waves. At higher frequencies, complex modal behaviour evidently occurs.

The curves shown in Figs. 11a and 12a show



(a)

(b)

Fig. 12 – Plots of velocity vs. position at constant frequency for a low-frequency drive unit.
(a) magnitude (logarithmic scale: curves displaced by 10 dB);
(b) phase. Each curve is identified by the excitation frequency. Vertical spacing between plots is for clarity only.

the variation of surface velocity with frequency and position respectively, but not the absolute magnitude of this quantity. Measurements using a stationary reference surface, on the other hand, provide a measure of surface movement in absolute terms (i.e. in terms of the wavelength of the light in use). If required, this absolute measurement may be used to calibrate the measurements of surface velocity obtained using a moving reference surface.

To date, the Michelson interferometer with moving reference surface has provided much valuable insight into the behaviour of loudspeaker diaphragms, and has proved to be of great assistance in developing the low-frequency drive unit of the LS 5/9 monitoring loudspeaker.[15] In its present form, however, the equipment is not convenient in use, and the results have to be assembled by hand for the presentations shown in Figs. 11 and 12.

With the addition of electronically-controlled scanning mirrors, the equipment could be placed under the control of a microcomputer, which could also process the measurement results from presentation in any required form. In their work, Banks and Hathaway[7] have presented two-dimensional displays of velocity in isometric form, showing the complete behaviour of the loudspeaker diaphragm at a single frequency. By making use of the phase information they have also provided an animated display which is helpful in interpreting complex modal behaviour. Clearly, by the use of a microcomputer any required form of display would be readily available, and could be stored on disc for future reference.

One final aspect of the optical system deserves mention. Although the use of a rotating motor spindle to provide a moving reference surface has the advantage of simplicity, it would in practice be difficult to achieve high reference-surface velocities by this method, thus in turn limiting the maximum surface velocity that can be measured. For most purposes, however, this limitation is not important. Nevertheless, by using instead a quartz crystal or a magnetostrictive rod oscillating at ultrasonic frequency (i.e. more than twice the upper frequency of measurement) instead of the rotating spindle, much higher peak velocities can be measured, at the expense of only slight additions to the demodulating circuitry. By this means the mechanical construction could also be simplified, with resultant gains in reliability and robustness.

In general, it may be seen that the Michelson interferometer can be a very powerful tool in loudspeaker development, providing as it does a degree of insight into diaphragm behaviour that is not available by any other means.

5. Conclusions

Interferometric methods of surface movement measurement rely on the direct or indirect observation of the interference patterns produced when coherent radiation reflected from the surface in question is combined with radiation from the same source which has travelled along a reference path.

Holography and speckle-pattern interferometry both involve reflection of light from the entire surface and provide an overall indication of the behaviour of the surface in terms of a fringe pattern in the case of holography, or regions of speckle-pattern visibility and invisibility. In both cases the resulting information does not directly indicate the precise characteristics of the surface movement, although the node-antinode pattern of the vibrating surface may be seen. Speckle pattern interferometry gives an immediate visual indication of this characteristic, whereas holography involves the delay required for processing the medium (usually photographic film) on which the hologram is recorded. In both cases precautions are required to eliminate unwanted surface movement: this is difficult in the case of a large, light and relatively freely mounted object such as a loudspeaker diaphragm. Furthermore, the presence of a travelling-wave mode of surface vibration may sometimes give rise to movement over most of the surface, thus obscuring the node-antinode pattern. Holography and speckle pattern interferometry do not, therefore, appear well-suited to the investigation of the vibrational behaviour of loudspeaker diaphragms.

The Michelson arrangement has been chosen for point-to-point interferometric measurement of surface movement because of its economy of optical components and also because of the well-defined direction in which surface motion is measured. This method of measurement gives results directly in terms of surface displacement (using a stationary reference surface) or velocity (using a moving reference surface or other method of reference radiation frequency-shift). In the latter case, especially, the surface motion is large compared with the radiation wavelength and no precautions against spurious surface movement are necessary. In this case the measured quantity is in the form of frequency modulation of a high-frequency carrier (of the order of a few megahertz). This, together with the use of tracking filter techniques, enables signals representing the magnitude and phase of surface velocity to be obtained which have an adequate signal-to-noise ratio for measurement purposes. For example, a signal-to-noise ratio of better then 45 dB has been obtained when the loudspeaker unit under measurement was operating well within its maximum power-handling capability. Without the use of a moving reference surface a "fringe counting" technique may be used, but in this case phase information is subject to an ambiguity of 180°. Furthermore the surface movement may only be an order of magnitude greater than the wavelength of the light in use, and "ambient" vibration will assume greater importance. However, the fringe counting technique gives "absolute" results (the measurements are in terms of the wavelength of the light used), and may if required be used to calibrate the velocity measurements described above.

Experience gained using the equipment described in this Report has shown the usefulness of scanning techniques, in which measurements are made at one frequency along a radius of the loudspeaker unit. These techniques could be extended to include two-dimensional scanning of the complete unit, and possibly the provision of an animated display of vibrational behaviour.

The use of a moving surface in the form of a rotating cylinder to obtain the frequency shift of the reference radiation has proved to be simple and convenient. Some measurements of surface movement may however require a rather greater frequency shift (or in other words a reference surface moving at a rather higher velocity) than can conveniently be obtained using this technique. The use of an oscillating reference surface may be more convenient in such cases.

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